

**LOW-CA PYROXENE IN AMOEBOID OLIVINE AGGREGATES IN PRIMITIVE CARBONACEOUS CHONDRITES.** Alexander N. Krot<sup>1\*</sup>, Mikhail I. Petaev<sup>2</sup>, and Hisayoshi Yurimoto<sup>3</sup>, <sup>1</sup>Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA (sasha@higp.hawaii.edu); <sup>2</sup>Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA (mpetaev@cfa.harvard.edu); <sup>3</sup>Earth and Planetary Sciences, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan (yuri@geo.titech.ac.jp).

**Introduction:** Amoeboid olivine aggregates (AOAs) are aggregates of nebular gas-solid condensates which appear to have experienced high temperature annealing without substantial melting [1]. In primitive carbonaceous chondrites, AOAs consist of forsteritic olivines, FeNi-metal, and refractory materials composed of Al-diopside, anorthite, spinel, and very rare melilite. Primary minerals in AOAs are <sup>16</sup>O-rich ( $\Delta^{17}\text{O} < -20\text{‰}$ ), suggesting formation in an <sup>16</sup>O-rich gaseous reservoir [2-5]. Although thermodynamic calculations at  $10^{-3} - 10^{-6}$  bar total pressure [6-8] predict condensation of enstatite by reaction between  $\text{SiO}_{(\text{gas})}$  and forsterite at  $\sim 50-80$  K below the condensation temperature of forsterite, no low-Ca pyroxenes in AOAs have yet been identified. Here, we report a discovery of low-Ca pyroxene in AOAs from CV, CR, CM, and ungrouped carbonaceous chondrites Adelaide and Acfer 094.

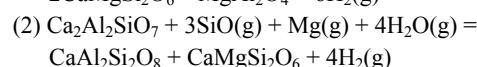
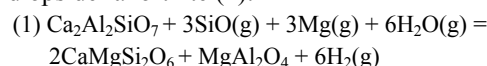
**Samples and Analytical Techniques:** More than 100 polished sections of the reduced CV, CO, CM, CR, CB, CH, CK, and the ungrouped carbonaceous chondrites Adelaide and Acfer 094 were mapped in Mg, Ca, Al, Ti, and Si K $\alpha$  X-rays with a Cameca SX50 electron microprobe. AOAs identified with combined X-ray maps were studied in backscattered electrons (BSE) with a JEOL 5900LV scanning electron microscope. Mineral compositions were determined with a Cameca SX50 electron microprobe. Oxygen isotopic compositions were measured with a Cameca 1270 ion microprobe at TiTech; analytical procedures for O-isotopic measurements are described in [9].

**Results:** AOAs in primitive (unmetamorphosed and unaltered) carbonaceous chondrites consist of forsteritic olivine ( $\text{Fa}_{<1}$ ), FeNi-metal, and variable amounts of spinel, diopside,  $\pm$ anorthite, and exceptionally rare melilite. Melilite is replaced by a fine-grained mixture of spinel+Al-diopside and by anorthite. Spinel grains appear to be replaced by Al-diopside and anorthite. Plagioclase is nearly pure anorthite. High-Ca pyroxenes (Al-Ti-diopside) have large variations in  $\text{Al}_2\text{O}_3$  (0.5-16 wt%) and  $\text{TiO}_2$  (0.1-7 wt%) contents; the aluminum content in Al-diopside increases towards spinel or anorthite. Most high-Ca pyroxenes are MnO-free ( $<0.07$  wt%) and  $\text{Cr}_2\text{O}_3$ -poor ( $<0.2$  wt%).

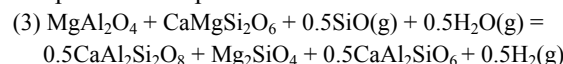
Ten out of  $> 500$  AOAs studied contain low-Ca pyroxene ( $\text{Fs}_{1-4}\text{Wo}_{2-5}$ ), which occurs in the outermost portions of the AOAs and replaces olivine (Figs. 1, 2). Oli-

vine in these AOAs is commonly enriched in MnO (up to 0.8 wt%),  $\text{Cr}_2\text{O}_3$  (up to 0.6 wt%) and fayalite ( $\text{Fa}_{1-4}$ ) relative to AOAs without low-Ca pyroxene (MnO and  $\text{Cr}_2\text{O}_3 < 0.3$  wt%). Low-Ca pyroxenes have high  $\text{Cr}_2\text{O}_3$  (up to 1 wt%) and MnO (up to 0.5 wt%) contents. Some of these pyroxenes have abundant inclusions of FeNi-metal. Forsteritic olivine in the CR AOA (Fig. 2) is <sup>16</sup>O-rich ( $\delta^{17,18}\text{O} \sim -40\text{‰}$ ), whereas its low-Ca pyroxene is <sup>16</sup>O-poor ( $\delta^{17,18}\text{O} \sim 0\text{‰}$ ).

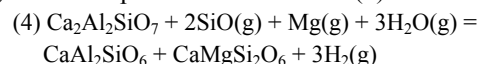
**Discussion:** We infer that like AOAs without low-Ca pyroxene, those with low-Ca pyroxene originally formed in the CAI-forming regions, characterized by <sup>16</sup>O-rich composition of the nebular gas, as aggregates of gas-solid condensates largely composed of forsterite, FeNi-metal, spinel, diopside,  $\pm$ anorthite,  $\pm$ melilite. Melilite was later replaced by spinel $\pm$ Al-diopside (1) or by diopside+anorthite (2):



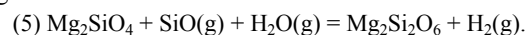
Additional anorthite could have formed by reaction between spinel and diopside:



The observed increase of Al content in high-Ca pyroxenes towards spinel grains in melilite-free/poor CAIs may have resulted from reaction of spinel with diopside (3) or from replacement of melilite (4):



The presence of <sup>16</sup>O-poor low-Ca pyroxene replacing olivine in the outermost portions of several AOAs, and relatively high abundances of moderately volatile elements, such as Mn and Cr, in these AOAs points to a formation of low-Ca pyroxene at relatively low nebular temperatures by reaction of olivine with an <sup>16</sup>O-poor gaseous reservoir, possibly in the chondrule-forming region:



The very rare occurrences of AOAs with low-Ca pyroxene may indicate that either AOAs were isolated from the hot nebular gas prior to condensation of low-Ca pyroxene or that reaction (5) was limited due to kinetical reasons [10]. If the latter is correct, then the common occurrence of Type I chondrules rich in low-Ca pyrox

enes may require either direct condensation of low-Ca pyroxenes/silica from fractionated nebular gas [11] or condensation of  $\text{SiO}_{(\text{gas})}$  into chondrule melts [12].

**References:** [1] Komatsu M. et al (2000) *MAPS* 36, 629-643. [2] Itoh S. et al. (2002) *LPS* 33, #1490. [3] Hiya-gon H. and Hashimoto A. (1999) *Science* 283, 828-831. [4] Krot A.N. et al. (2002) *Science* 295, 1051-1054. [5] Aléon J. et al. (2002) *MAPS* 37, 1729-1757. [6] Petaev M.I. and Wood J.A. (1998) *MAPS* 33, 1123-1137. [7] Yoneda S. and Grossman L. (1995) *GCA* 59, 3413-3444. [8] Ebel D.S. and Grossman L. (2000) *GCA* 64, 339-366. [9] Yurimoto H. et al. (1998) *Science* 282, 1874-1877. [10] Imae N. et al. *EPSL* 118, 21-30. [11] Krot A.N. et al. (2003) *LPS*, this vol. [12] Tissandier L. et al. (2003) *MAPS* 38, in press.

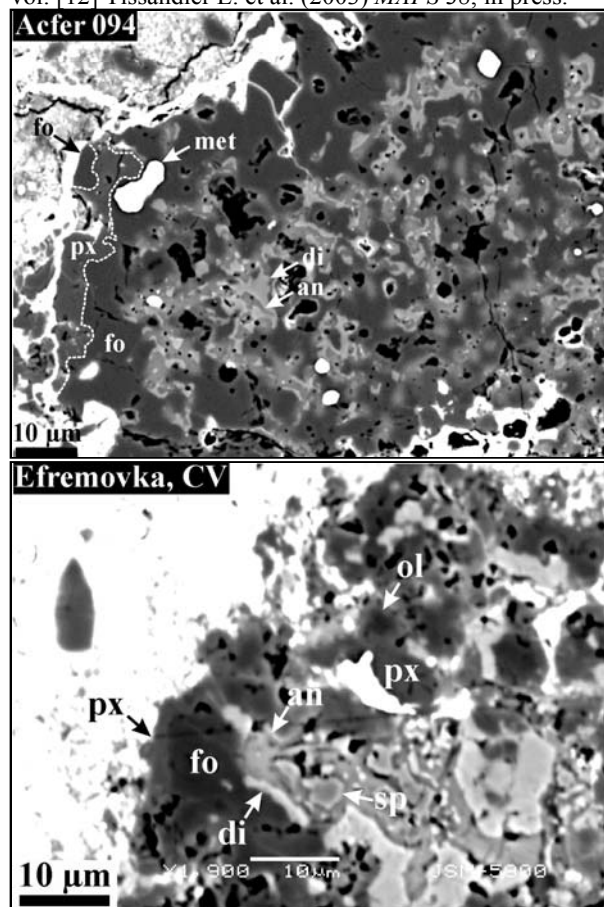


Fig. 1. BSE images of AOAs from the ungrouped carbonaceous chondrite Acfer 094 (top) and reduced CV chondrite Efremovka (bottom). AOAs consist of forsteritic olivine (fo), FeNi-metal (met), Al-diopside (di), anorthite (an), and spinel. Forsterite in outer portions of the AOAs is replaced by low-Ca pyroxene (px).

Fig. 2. Combined elemental map in Mg (red), Ca (green), and Al (blue) K $\alpha$  X-rays (a), elemental map in Si K $\alpha$  (b) and BSE image (c) of AOA from CR carbonaceous chondrite PCA91082. AOA is mineralogically zoned: its core contains abundant Ca-Al-rich phases (Al-diopside, anorthite, spinel: bluish); mantle zone consists of forsterite and FeNi-metal (black); outer zone consists of low-Ca pyroxene that replaces forsterite.

